NATURE AND PROPERTIES OF RED SOILS OF THE WORLD

V C BALIGAR[1], N K FAGERIA[2], H ESWARAN[3], M J WILSON [4] AND ZHENLI HE [5]

[1] USDA-ARS-ACSL, Beltsville Agricultural Research Center, Beltsville, MD 20704, USA
[2] EMRAPA/Arroz, e Feijao, Cx. P. 179, 75375-000 Santo Antonio de Goias, GO. BRAZIL
[3] USDA-NRCS, PO Box 2089, Washington, DC 20013, USA
[4] Macaulay Land Use Research Institute, Aberdeen, AB15 8QH, UK
[5] University of Florida, IRREC, Fort Pierce FL 34945, USA

ABSTRACT

Red soils are highly leached soils of the humid tropics having a high content of sesquioxides. In the current system of U. S. Soil Taxonomy, red soils are usually designated under the orders of Oxisols, Ultisols, and occasionally Alfisols, Mollisols and even Inceptisols. Red soils are predominantly found in South America, Central Africa, South and Southeast Asia, China, India, Japan and Australia. In general, these soils have good physical conditions for plant growth although they often have very low water-holding capacity. Low natural fertility is the main limiting factor for good crop production on these soils and they are frequently acidic and deficient in all essential nutrients, especially N, P, K, Ca, Mg, S, Zn, B, and Cu. Adequate applications of lime and fertilizers are important strategies for replenishing soil fertility and improving crop yields on these soils. In addition, cultural practices such as appropriate crop rotation, improvement of organic matter content, use of nutrient efficient or acid tolerant plant species or cultivars, and control of soil erosion can optimize nutrient use efficiency and improve crop yields on these soils. In China, utilization of red soils for crop production by farmers depends not only upon the employment of such practices but also upon socio-economic factors and the availability of adequate incentives.

1. INTRODUCTION

A variety of soil classification systems have been developed to describe the suitability of soils for specific types of land use and the natural ability of the soils to tolerate factors leading to their degradation. These inherent soil characteristics vary within and between continents, regions, and landscapes (Eswaran et al., 1999; Wander et al., 2002). Inherent differences in soil properties arise from the influence of the generally accepted factors of soil formation, namely climate, time, vegetation, parent material and topography. Early scientific endeavours identified the importance of

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categorizing soil type and soil variables or properties with regard to land use, especially for agricultural purposes (Carter et al., 1997). Red soils are recognized as important in soil classification systems because of the vast areas occupied by these soils in various parts of the world and because of the great possibilities that they offer for agricultural production. Hence, it is important to provide a global overview of the nature and properties of these soils and to consider the red soils of China in this context.

Even in early classification systems, the red colours of some soils were used as a defining characteristic to separate them from other soils. The terms laterites, latosols or merely red soils are found in early literature. Modern soil classification systems use morpho-genetic characteristics to differentiate soils, particularly at the higher categorical levels. At lower levels, use-related properties are used. In Soil Taxonomy (Soil Survey Staff,1999), red soils may be present in many soil Orders, such as Alfisols, Oxisols, Ultisols and Inceptisols. However, only a very pronounced red colour is used to define some soils. Using Alfisols as an example, the great group of Rhodoxeralfs or Rhodustults are distinguished by their intense red colours. These soils have a Munsell colour of 2.5 YR or redder, as well as meeting other requirements Red soils are usually highly leached with a high clay content, and frequently occur in deep profiles that are low in silica and high in sesquioxides. They are mostly found in tropical and sub-tropical areas (Soil Science Society of America, 1996) and are the third most important soils of the world covering 13 percent of the land area. In general, red soils often have deep profiles with good physical properties for crop production. However, their water holding capacity is often poor and as the soils frequently occur in areas subject to droughts at certain times of the year, this can be a serious limitation for crop production. Red soils are generally acidic in nature and deficient in most essential nutrients. Hence, liming and use of adequate fertilization are important management practices to improve or obtain good crop yields on these soils. Sehgal (1998) states that the major constraints for crop production on these soils are: poor water holding capacity, surface crusting, as well as chemical constraints such as acidity, toxicity because of high levels of Al and Mn and nutrient deficiency (P, K, Ca, Mg, Zn). Sehgal et. al (1998a and b) provide extensive coverage of various aspects of the red and lateritic soils of the world, in particular their distribution, properties and management for sustainable agriculture.

2. PREDOMINANT RED SOILS OF THE WORLD

As there is no database on red soils *per se,* the map in the coloured plate at the beginning of the book shows the distribution of soil suborders with red soils. By definition, the Oxisols have a clay fraction dominated by low activity clay minerals

and are highly weathered. Most Oxisols are red but there are Oxisols that are yellow (Xanthic Hapludox) and some Aquoxs are even white or pale-coloured. The red Alfisols are dominated by red Mediterranean soils (Rhodoxeralfs) but they may be red under other moisture regimes if the parent rock has a high amount of sesquioxides and the weathering intensity is advanced. The red Ultisols show similar relationships.

Table 1 shows the areas of the various sub-orders of Oxisols, Ultisols and Alfisols that have red soil members. The extent of such soils on each of the major continents is shown, as well as an estimate of their global occurrence. Approximately 80% of the Oxisols, 60% of the Ultisols and 40% of the Alfisols may be considered to be red soils for most purposes. The total area of such red soils amounts to about 13.24 million Sq. Km, which is about 47% of the combined area of the Oxisols, Ultisols and Alfisols. As shown on the map, most of these soils occur in the tropics.

Table 1. Areas (thousands km^2) of red soil orders and sub-orders in the world

Order/ Continent	Oxisols				Ultisols				Alfisols			
	Ustox	Perox	Udox	Total	Udult	Ustult	Xerult	Total	Ustalf	Xeralf	Udalf	Total
North America	0.36	-	-	0.36	854.1	131.0	16.0	1001	349.6	176.0	813.8	1337
South America	1339	1096	3402	5757	851.8	1091	0.02	1953	998.9	25.3	673.6	1698
Central America	1.30	0.67	5.72	7.69	95.2	58.9	-	154.1	22.6	-	56.3	78.9
Europe	-	-	-	-	3.53	-	-	3.53	253.8	118.8	478.0	850.7
Africa	1719	87.2	1757	3557	607.6	1649	0.93	2258	2471	80.1	167.3	2718
Asia	18.5	50.4	72.1	141	2981	825.6	2.67	3808	1084	209.4	304.6	1598
Australia/ Oceania	39.2	1.12	20.0	60.4	84.7	101.3	-	186.0	501.7	270.5	225.1	997.3

Ultisols (Acrisols) and Oxisols (Ferralsols) have common nutrient management problems. In general, both these groups of soils have a low to very low water-holding capacity and, due to the aggregation of the clay fraction, a rather high permeability. In semi-arid environments, or in climates with a distinct dry season such as in sub-tropical areas of China, these soils suffer from moisture stress. Kaolinite dominates the clay fraction, sometimes with significant amounts of poorly ordered material. A high sesquioxide content often means that Oxisols and Ultisols have a high variable charge, with a zero point of net charge close to 6. At the pH of the soil, the sub soils of some of these soils have a net positive charge, whereas the top soil,

which contains some organic matter, has a negative charge. One of the critical management factors in such soils is the maintenance of the organic matter content. Erosion and loss of organic matter exposes the high ZPNC materials at the soil surface and in such situations leaching of cations is rapid and is accompanied by a high capacity for fixation of anions such as P. It may be noted, however, that the Alfisols, even the red ones, have a mixed mineralogy and do not have all the yield-depressing features of the red Ultisols and Oxisols. The same is true for the red soils that are occasionally found in the Mollisol and Inceptisol Orders. However, in the three major red soil orders, and specifically in the Ultisols and some of the Alfisols in humid environments, the top soil is acid. In many of the soils, aluminium may account for more than 60% of the total acidity and this condition depresses growth in most plants. Soil acidity is a major challenge to the management of these soils as root growth is restricted. When the soil is subject to moisture stress under drought conditions, the impact on crop growth becomes even more devastating.

For more details on red soils, readers are referred to excellent papers by Baligar and Ahlrichs (1998), Dudal (1976), Eswaran et al. (1997), Sanchez (1976), Sanchez and Isbell (1978), Sehgal et al. (1998a and b), Von Uexkull and Mutert (1995), and Van Wambeke (1992) for more extensive coverage on this topic.

3. NATURE AND PROPERTIES OF RED SOILS OF SELECTED REGIONS

3.1 Red Soils of Brazil and Argentina

Red soils in Brazil are found in the central part of Brazil, locally known as the "Cerrado", which covers about 205 million ha (23%) of the land area of Brazil. Most of the soils in this region are highly weathered Oxisols (46%), Ultisols (15%) and Entisols (15%), with low natural soil fertility, high aluminum saturation and high phosphorus fixation capacity. At present roughly 10 million ha of rainfed crops are grown with an average yield of 2 t ha^{-1} and a total production of 20 million tons of grains. The irrigated area is rather small, only 300,000 ha with an average yield of 3 t ha^{-1}, but still produces over 0.9 m tons of grain (Macedo, 1995), about 25% of the soybean, rice, and corn harvest and 14% of the bean harvest of Brazil. In addition, coffee production in this region accounts for 20% of the national production. Improved pasture covers 35 m ha of the red soil land area of Brazil and supports 53 m head of cattle, producing 40% of Brazil's beef (1.7 m tons) and 12% of its milk supplies (Macedo, 1995).

It is estimated that 50% of the Cerrado area is of potential use as arable land. The climate also favours crop production with a mean annual rainfall of about 1500 mm and a mean annual temperature of 22°C in the south of the region and 27°C in the north (Goedert, 1989). Clearly, therefore, the Cerrado has a very high potential for

agricultural production if only the main yield limiting factors of low soil fertility and high soil acidity could be overcome. Chemical properties are good indicators of the fertility status and nutrient supplying power of a soil for crop production and Table 2 shows the average chemical properties of Oxisols. These soils tend to have a rather low pH, with low levels of P, K, Ca, Mg and Zn and with a poor organic matter content. Usually, they are too poorly base saturated to sustain annual crop production. Fertilizer and liming recommendations are generally made on the basis of soil chemical analyses, always bearing in mind that optimum soil test values for macro and micro-nutrients vary from soil to soil, crop to crop, and extractant to extractant. In the Cerrado soils of Brazil, limiting values for P should be >10 mg kg^{-1}, for K >50 mg kg^{-1}, for Ca >2 $cmol_c$ kg^{-1}, for Mg >1 $cmol_c$ kg^{-1}, and for S >12 mg kg^{-1}.

Table 2. Mean chemical properties of surface samples (0-20cm) of Oxisols from the State of Mato Grosso, Brazil in the Cerrado region

Range	H_2O	(%)	mg dm^{-3}		$Cmol_c kg^{-1}$			mg dm^{-3}			
	pH	O.M	P	K	Ca	Mg	Al	Cu	Zn	Fe	Mn
Minimum	4.8	0.8	0.6	12	0.54	0.22	0.0	0.2	0.3	30	2
Maximum	6.3	3.1	14.8	73	3.42	2.42	0.4	1.0	8.7	131	13
Median	5.5	2.2	4.1	32	1.77	0.84	0.2	0.5	2.4	62	5

At such levels of nutrients satisfactory yields of most annual crops can be produced (Fageria, 1992). Critical values for micronutrients on these soils so as to produce satisfactory annual crops are: Fe 2.5-5 mg kg^{-1}, Mn 4-8 mg kg^{-1}, Zn 0.8-5 mg kg^{-1}, B 0.4-3 mg kg^{-1}, Cu 0.8-3 mg kg^{-1} and Mo 0.2-0.5 mg kg^{-1} (Fageria, 1992). With an organic matter content of about 3-4%, base saturation between 50-60% and pH between 5.5 – 6.5, it is possible to produce good yields of most annual crops on these soils (Fageria et al., 1997a).

The red soils of Argentina mostly fall into the Oxisol, Ultisol , Alfisol and Mollisol orders. They occur in the north-east corner of the country bordering Brazil and Paraguay and cover an area of 2.4 m ha (0.8 %) of the national land area (Scoopa and Godagnone, 1998). As in Brazil, the soils classed in the Oxisol and Ultisol orders are low in inherent fertility and contain high amounts of exchangeable Al. They also contain elevated contents of Fe oxides and are highly P fixing in nature. Most of these soils are situated on steep slopes and, as torrential rains are common, they often require protection from water erosion by terracing and contour ploughing is advised. Liming and P fertilization is needed to produce satisfactory yields of maize, banana and tobacco. Table 3 shows that in tropical Latin America as a whole many of the important chemical properties of Oxisols, Ultisols and Alfisols are similar to the Oxisols of Brazil.

Table 3. Mean chemical properties of surface samples (0-20cm) of tropical Latin American red soils

Soil Order	Clay (%)	pH	O.C (%)	Ca	Mg	K ($cmol_c kg^{-1}$)	CEC	Al Sat (%).
Oxisols	40	4.6	1.9	0.3	0.3	0.08	14.0	70
Ultisols	30	4.5	1.6	0.9	0.4	0.17	2.6	65
Alfisols	30	5.3	1.0	6.5	3.5	0.50	17.5	15

Source: Sanchez and Isbell, 1978

3.2 Red Soils of Kenya

Red soils along with lateritic soils occupy close to 14.4 m ha of land, constituting about 25% of the area of Kenya (Kiome and Muchena, 1998). The red soils are generally deep and well- drained. The red color is caused by a predominance of hematite over goethite. The red soils are mostly classed as Nitosols, Luvisols and Acrisols under the FAO scheme, selected soil properties being shown in Table 4.

Table 4. Selected properties of surface samples (0-20cm) of some red soils in Kenya (after Kiome and Muchena, 1998)

Horizon	Organic C (%)	Clay (%)	pH (H_2O)	CEC ($cmol_c kg^{-1}$)
A	1.7 – 4.5	42 – 72	-	14 - 39
B		62 - 80	5.3 – 6.2	

The Nitosols are deep soils (> 150 cm) with good water holding capacity and drainage. These soils have pH of 4.5 to 6.5, with CEC of 16 to 39 $cmol_c kg^{-1}$,are very productive soils and are used for growing coffee, tea and horticultural crops. To maintain production on these soils, conservation practices and fertilization are necessary. The Luvisols have a low SOM content in the surface horizon and a high clay content in the subsurface horizon with high bulk density (1.4 to 1.6 g cm^{-3}). These soils are high in K and micronutrients, but are low in N. Application of fertilizers, manure, green manure and protection from soil erosion are the major issues for maintaining the productivity of these red soils. The Acrisols soils have a high CEC (20 $cmol_c kg^{-1}$) with base saturation of~50%. Additions of fertilizer, manure and lime are needed to maintain

the productivity of these soils.

3.3 *Red Soils of India*

The red soils in India occur mostly in southern and semi-arid regions and occupy an area of 61.5 million ha (Bhattacharyya, 1992). They fall mainly into the Alfisol order, usually being classed as Rhodustalfs (Luvisols). Some of the properties of these soils are shown in Table 5. It can be seen that the soils are low in organic matter and have a low CEC. However, they are not as acid as many red soils and according to Bhattacharyya (1992) the normal red loam soils have a pH around neutrality or else slightly on the acid side. The red soils may become lateritic with depth. This means that the sub-soil is highly enriched with Fe and/or Al and becomes hard enough to make bricks upon exposure to alternate wetting and drying (Sehgal 1998). The parent materials of these soils are usually granite, weathered gneiss or sandstone and their clay fractions are predominantly kaolinitic (Sehgal et. al, 1998c). These soils are often subject to severe water erosion and nutrient losses due to excessive rainfall (600 to 4000 mm/year). Deficiencies of N and P

Table 5. Selected properties of red soils of India. (from Sehgal et al, 1998c)

Horiz	Color (hue)	Texture (USDA)	pH (KCl)	pH (H_2O)	O.C (%)	CEC ($Cmol_c kg^{-1}$)
Ap	2.7/ 4.5YR	Sl, ls, Scl	5.3	5.5-6.6	0.21- 1.15	2.0 - 11.6
B, Bt	2.5/ 5.0YR	Scl, Sc-c, SiC, cl	6.0	5.2-7.3	0.12 - 0.62	3.4 – 15.4

are widespread but K is only deficient in certain areas (Bhattacharyya, 1992). Major constraints for crop production on these soils are: severe soil erosion (nutrient leaching), low water holding capacity (leading to frequent drought conditions), deficiency of N, P and K, low availability of P (high P fixation), coarse soil texture and sometimes excess soil acidity (Sehgal et. al, 1998c). These constraints are identical to those found for the red soils of China. With proper management, the Indian red soils can produce high yields of plantation crops (coffee, tea, cacao, aracanut, oil palm, coconut); horticultural crops (mango, citrus, cashew, pine apple), field crops (rice, legumes) and spices. Restoration of organic matter status and alleviation of soil acidity, nutrient imbalances, moisture status and moisture stress are the major challenges in bringing these soils under productive and sustainable farming

(Sehgal et. al, 1998c).

3.4 Red Soils in south-east Asia

Bangladesh

Red soils occupy about 16% of the total land area of Bangladesh (Saheed, 1992), an area of 1.9 m ha. They occur in a variety of topographic situations ranging from the hilly outliers of the Assam Hills in the north and north eastern parts of the country (1.8 m ha) to river terraces on uplifted fault blocks in the central part of the country (1.2 m ha). The red soils of the hills are highly acidic (pH 4.4 to 5.3), strongly leached, of poor base status and may have an argillic horizon. Segregations of Fe and Mn in plinthic formations may be present in some of the older soils. These red soils have been placed into the Ultisol order and include Paleustults, Haplustults and Plinthustults. Red soils on the terraces have developed on clay formations in a landscape that has been tectonically uplifted, deeply dissected and consequently well-drained. In these circumstances strongly acidic (pH 4.6 to 5.4), kaolinitic, deep red soils have formed. They are mainly classed as Ultisols, but where the base status of the argillic horizon is greater than 35% they have been placed in the Alfisol order. The red soils of the hills are used mainly for tea, rubber and also for horticultural purposes, whereas the terrace soils support a much wider variety of crops, including rice, cowpea, mustard and groundnuts. These soils respond well to irrigation and fertilization (Rahman, 1992).

Thailand

According to detailed soil maps, red soils in Thailand occupy an area of 5.12 m ha or 10% of the country, but this excludes the mountain areas where soil survey is incomplete, comprising 15.71 m ha or a further 31.6% of the country's area (Moncharoen, 1992). These mountain areas are for the most part dominated by red soils. Most of the red soils have been classified in the Ultisol, Oxisol and Alfisol orders. The Ultisols are of the most widespread occurrence, occupying an area of 3.68 m ha, with Ustults, Umults and Humults being the most common soil types. The properties of these soils are quite varied, reflecting differences in parent materials, climate and positions in the landscape. Most are low in organic matter (<1%), except for the Humults, and tend to be acidic, ranging in pH (H_2O) from 4.1 to 5.5. Percent base saturation tends to be less than 35% although higher values may be recorded at the surface and at depth. The Thai Ultisols vary greatly in clay content (2.5 to 81%) but the mineralogy appears to be largely kaolinitic. Oxisols are found only in areas associated with basalt flows and are of restricted occurrence. The soils are thick and clayey and belong to the Haplustox and Haplorthox great groups. They are acidic (pH <5.5), poorly base saturated (<20%), poor in organic matter and largely kaolinitic. The red soils classed as Alfisols in Thailand occur mainly in the north of the country where the parent materials are limestones and other basic rocks. The influence of the

parent material means that the soils may be only slightly acidic or even alkaline in reaction, with pH values ranging between 5.6 to 7.4.
(Moncharoen, 1992), and that they may be well or even fully base saturated. Clay contents are usually very high with a kaolinite-dominated mineralogy. The potential for agricultural usage of red soils in Thailand is highly variable and relates particularly to differences in biophysical conditions. Lowland red soils with a high clay content may be cropped with corn, sorghum, cotton and beans. In areas of high rainfall, rubber and fruit trees are the most extensive crops, while in the northern mountain areas tea and coffee are grown. Constraints on crop production on the Ultisols are similar to those summarised previously and include excess acidity with attendant problems of aluminium toxicity, low content of available nutrients major nutrients, poor water holding capacity related to a kaolinitic clay mineralogy, as well as susceptibility to erosion. These constraints do not necessarily apply to the Alfisols.

Malaysia
Red soils are widespread in peninsular Malaysia. About 70% of the country's soils are classed as Ultisols or Oxisols (Wahab and Zahari, 1992), although not all are considered to be red earths or red soils. However, the red soils are always highly acidic (pH 4.2 to 4.8), high in Al saturation (60 to 90%), and low in cation exchange capacity (< 5 meq/100g). The soils are deficient in all the major nutrients and fix large amounts of P. Water availability is rather low, drainage can be excessive and moisture stress can be a problem during dry seasons. Despite these constraints, the red soils are considered as Class 1 or Class 2 soils as they can be successfully used to plant rubber, oil palm cocoa and tropical fruit trees.

Indonesia
The red soils in Indonesia have been divided into so-called red-yellow podzolic soils, red-yellow Mediterranean soils and latosol/lateritic soils (Sudjadi et al, 1992).The red- yellow podzolic soils are found on a variety of acidic to intermediate parent materials and occupy an area of 51 m ha, or about 30% of the Indonesian land area.They are found mainly on the islands of Sumatra, Kalimantan, Sulawesi and Irian Jaya. Typically, they are very acid with high levels of exchangeable Al, deficient in all the major plant nutrients and low in organic matter. The soils are often used for shifting cultivation or for semi-permanent subsistence agriculture, but large areas are also used for ree crops (rubber, oil palm) and with good management food crops such as rice and cassava can also be grown. In Soil Taxonomy the red-yellow podzolic soils correspond to Ultisols, Oxisols and occasionally Inceptisols. The red-yellow Mediterranean soils are found mainly on limestones, calcareous sandstones and volcanic material, particularly in the dry areas of the Indonesian archipelago, and occupy a total area of 8.5 m ha. Because of their derivation from basic material, these

soils have pH values ranging from 6.5 to 7.5 and are often highly base saturated. However, they are low in organic matter and because of their heavy texture may be poorly drained. Nevertheless, they are inherently more fertile than the red-yellow podzolic soils and are cultivated with a wider variety of crops, including maize, cassava, peanuts and rice. They correspond to Alfisols in the US Soil Taxonomy. Latosols and lateritic soils occupy 18 m ha in Indonesia. They are found mainly on volcanic parent materials and are deeply weathered, strongly leached and highly acidic (pH 4.5 to 5.5). They are low in organic matter and deficient in nutrients. However, their physical properties may be good; they are easily worked because of their friable consistency and they are more resistant to erosion because of their high degree of aggregate stability. They are used for the cultivation of upland crops or wetland rice and are classed as Oxisols or Inceptisols.

Vietnam

Weathering under humid tropical climatic conditions has resulted in the formation of reddish infertile soils in Vietnam. These soils cover an area of 21.6 m ha, which is 2/3 of the country and are found from 20 m to 3400 m above MSL (Toan, 1998). The soils have high levels of sesquioxides in various forms of Fe and Al and have lost most of their bases and SiO_2 due to leaching. Precipitated Fe and Al compounds may form into subsurface hard pans. The reddish yellow ferrallitic soils, which occupy nearly half of the land area of Vietnam, have pH (KCl) values between 4.0 to 4.5, with high Al saturation and low P, mostly associated with Al and Fe. Reddish and yellowish soils in the northern mountainous areas have pH values in the range 4.1 to 4.8, CECs of 3.8 to 18.2 $cmol_c\ kg^{-1}$, available Ca from 0.51 to 8.0 $cmol_c\ kg^{-1}$ and available P from 0 to 1.4 mg kg^{-1} (Toan, 1998). Soil erosion, shifting cultivation, high P fixation and poor nutrient status are the major constraints for crop production on these soils.

3.5 Red Soils of China

Red soils are widely distributed in tropical and subtropical China, occupying an area of 0.45 million km^2 (Zhao, 1996). These soils include latosols, lateritic red soils, red earths, yellow soils, and red paddy soils derived from these zonal soils (Xiong and Lu, 1996). They are mostly equivalent to Oxisols, Ultisols and some of the Alfisols in the soil taxonomy of USA. The distribution pattern of land use in the red soil regions has been calculated as follows: arable 13.6%, forestry 44%, grassland 3.7%, wasteland 24% and others 14.7%.

The red soil regions in China have favorable climatic and biological resources, with an annual mean daily temperature of 17-20 ^{0}C and active cumulative temperature (> 10 ^{0}C) of 5400 to 6000 degree-days, mean annual duration of sunshine of 1500-1900 hours and mean annual solar irradiation of 420-460 MJm^{-2}. Annual rainfall ranges from 1300 to 1700 mm with a distinct peak in spring (March - May) and early

summer (June-July) followed by a late summer and autumn drought. Owing to the highly diversified physical conditions and abundant water, favourable temperature, adequate land mass and biological resources, these regions contribute greatly to the development of sustainable agriculture and to the economy of the country as a whole. Thus, 42.7% of the grain and 75% of the total rice are produced in these regions of China which supports 43% of the country's population, but accounts for only 27% of the nation's total cultivated land area (He et al., 2001).

The inherent fertility of Chinese red soils varies greatly, depending on parent materials, climate, and land use (Xiong and Lu, 1996). Organic matter contents in the red soils ranges from less than 10 g kg^{-1} to higher than 100 g kg^{-1}. Most red soils are generally low in organic matter although some yellow earths (which are often considered to be in the same category as red soils in China because they are thought to be closely associated from a genetic point of view) might contain over 100 g kg^{-1} organic matter. The yellow earths, which are mainly under forest vegetation in the mountainous regions of tropical and subtropical China, generally contain higher organic matter than latosols and red earths. Deforestation or prolonged intensive cultivation of upland crops has resulted in decreased content of organic matter, whereas land use change from upland cropping to submerged paddy rice-growing increased the organic matter in the soils. Application of farm manures also increases the soil organic matter content, but growth of green manure might have a negative effect (Xiong and Lu, 1996). Most red soils have low total N, due to their low organic matter content. Nitrogen deficiency is very common in the red soil regions, especially in the upland cropping systems. However, both total and available N in red soils tend to increase in southeast China due to increased inputs of fertilizer N and the return of straws to the soil. This trend is most obvious in the red soils under rice growth, and results from organic matter accumulation in these soils. Most red soils have a low content of P, but a high adsorption capacity for P due to their high contents of Fe and Al oxides and kaolinite. Approximately 60% of the agricultural red soils examined were deficient in available P in the early 1980's. This situation was improved by application of P fertilizers. However, 30 to 50% of these soils are still deficient in available P (Olsen-P) and contain <5 mg P kg^{-1} soil, which is the critical level. Intensive weathering, leaching and soil erosion combine to ensure that the K content in Chinese red soils is usually very low. More than 50% of the red soils examined had available K (neutral ammonium acetate extractable) below the critical level of 50 mg K kg^{-1}soil. K deficiency in red soils, especially red paddy soils, tends to increase with time because of unbalanced fertilization (high N and low K).

It may be noted that not all red soils in China are as inherently infertile as those described above. Thus, in Yunnan Province recent work by Yunnan Agricultural University in conjunction with various EU partners on red soils either derived from or strongly influenced by limestone, shows that these soils may be neutral or even slightly alkaline in reaction and may be fully base saturated. Moreover, they may have appreciable contents of weatherable minerals, including carbonates, and have a clay

fraction dominated by an illite/chlorite assemblage which is inherited from parent rocks. The soils in question occur on steep eroding slopes in a relatively young landscape, still subject to active tectonic movement, and are essentially colluvial in nature. Despite their deep red colour, it is probable that these soils would be included in the Alfisol or even the Inceptisol order.

4. MANAGEMENT STRATEGIES FOR IMPROVING CROP PRODUCTION ON RED SOILS WITH EMPHASIS ON BRAZILIAN SOILS

Infertile, nutrient-depleted red soils can be restored for crop production with appropriate management practices such as liming, use of adequate levels of deficient nutrients, control of soil erosion, increasing soil organic matter content, adoption of appropriate crop rotation and use of nutrient-efficient species and/or cultivars. Baligar and Fageria (1997), Fageria and Baligar (2001) and Fageria et. al (1990a) have written extensively on the management strategies aimed at improving nutrient efficiency in Oxisols and Ultisols.

4.1 Liming

Acidification represents a major degradation factor in the loss of soil quality and affects extensive areas in the tropical and temperate zones. Acid soils occupy 3.95 b ha (about 30%) of the world's ice-free land area (Von Uexkull and Mutert, 1995). In tropical South America, 85% of the soils are acidic, and approximately 850 m ha of under-utilized acid soils exist in this region. The poor productivity of crops grown on acid soils is due to a combination of toxicity (Al, Mn, H) and deficiencies of some major nutrients (N, P, K, Ca, Mg) and of some micronutrients (particularly Zn, Cu, B). Most Brazilian soils are acidic and suffer from the above deficiencies, with aluminum toxicity being recognized as one of the most important chemical constraints to crop production. Liming is the most common and the most effective practice for reducing these soil acidity problems. Liming significantly increased grain yields of annual crops grown on Oxisols (Fageria 2001) and led to a number of direct and indirect effects. The direct effects include higher levels of pH, Ca, Mg and base saturation (Table 6).

Liming also resulted in a number of changes that might be considered as indirect. Thus, as soil pH increased P and Mo become more available, whereas the availability of Mn, Cu, Fe and Zn decreased.

The quantity of lime added depends on type of soil, quality of liming material, crop species, cultivar (within species), and economic considerations. In Brazil, liming recommendations are based on the exchangeable Al, Ca, and Mg in the soil and lime requirement (LR) is calculated using the following formula:

$$LR \text{ (metric tons ha}^{-1}) = Al^{3+} \times 2 + [\, 2 - (Ca^{2+} + Mg^{2+}) \,]$$

Table 6. Influence of liming on soil pH, Ca, Mg and base saturation in the top 20 cm of an Oxisol of central Brazil (Fageria, 1998).

Lime applied ($t\ ha^{-1}$)	pH (H_2O)	Ca	Mg ($Cmol_c\ kg^{-1}$)	Base saturation (%)
0	5.5	1.5	0.9	36
4	6.1	3.6	1.2	64
8	6.5	3.6	1.3	66
12	6.7	4.3	1.3	68
16	6.8	4.4	1.3	68
20	7.0	4.9	1.4	75

The lime requirement computed from the exchangeable Al, Ca, and Mg content of the soil is based on the assumption that Al toxicity and Ca and Mg deficiencies are the most important growth-limiting factors in these acid soils. In some parts of Brazil, base saturation is used as a parameter to calculate lime requirement using the following formula:

$$LR \text{ (metric tons ha}^{-1}) = [CEC\ (B_2 - B_1) / (TRNP)] \times DF$$

where

CEC is the total exchangeable cations ($Ca^{2+} + Mg^{2+} + K^{+} + H^{+} + AL^{3+}$) in $cmol_c\ kg^{-1}$,
B_2 is the optimum base saturation,
B_1 is the existing soil base saturation,
TRNP is the total relative neutralizing power of liming material and
DF is the soil depth factor (1.0 for 20 cm, 1.5 for 30 cm depth).

For Brazilian Oxisols, the optimum base saturation for most annual crops is considered to be in the range of 50-60% (Raij and Quaggio, 1997).

4.2 Use of optimum rate of essential nutrients

Nitrogen deficiency is a major limitation to plant growth in acid soils in both tropical and temperate regions. In tropical America, N deficiency is a major soil constraint over 93% of the region occupied by Oxisols and Ultisols (Sanchez and Salinas, 1981). The main reason for the widespread N deficiency in these and other similar regions in

the tropics is a lower rate of N application than that removed in harvested crops or lost by other processes, combined with decreases in organic matter content with successive cultivation. Table 7 shows the response of rice and common bean crops to fertilization on Cerrado soils in Brazil. Phosphorus deficiency is a major yield-limiting factor for crop production on these soils (Fageria and Baligar, 1997b, Fageria and Baligar, 2001) because of their low native soil P content and their high P fixation capacity. The P fixation capacity of an Oxisol from central Brazil was studied over a period of 80 days by Fageria and Barbosa Filho (1987). It was concluded that the fixed P (not recovered by Mehlich solution extraction) increased from 45 to 268 kg P ha^{-1} when the P application rate was increased from 50 to 400 kg P ha^{-1}. This means these types of soils require large amounts of fertilizer P for optimum crop production. Annual crop responses to K fertilization are not as widespread and not as significant as N and P in the Cerrdao and Varzea soils of Brazil. Potassium, however, is absorbed in greater quantities by annual crops, especially by high yielding cultivars. A single upland rice crop grown on an Oxisol of Cerrado soil produced 4795 kg ha^{-1} of grains in about 130 days and took up 159 kg N ha^{-1}, 13 kg P ha^{-1}, and 189 kg K ha^{-1} (Fageria, 1998). This implies that in situations where intensive agriculture is practiced, failure to replace the K that is removed in the harvested crop can result in K deficiency becoming a limitation to further crop production. Responses of upland and lowland rice in Cerrado and Varzea soils in Brazil have been reported by Fageria et al. (1989, 1990b). Three management practices can be used to improve K fertilizer use efficiency by plants growing on these acid soils. First, K fertilizers should be applied at an economically feasible rate, bearing in mind the need, in the long term, to replace K lost through crop removal and leaching. Second, incorporation of crop residues in the soil after harvest enables a substantial amount of the plant K to be recycled. Approximately 85 to 92% of the total K content remains in the vegetative shoot of cereals such as rice and corn and 54 to 65% remains in the shoot of legumes such as common bean and soybean (Fageria et al., 1990a). Thirdly, the use of K-efficient cultivars will increase K uptake efficiency. Deficiencies of Ca and Mg are also important limitations to plant growth in Brazilian acid soils (Table 8). Thus, crops removed from about 26 to 53 kg Ca ha^{-1} and 12 to 26 kg Mg ha^{-1}, from a Brazilian Oxisol depending on the yield and the particular crop. Crop requirements of Ca and Mg in deficient soils can be fulfilled with the application of dolomitic lime. Data in Table 8 show an increase in exchangeable Ca and Mg in a Brazilian Oxisol when increasing rates of dolomitic lime were applied. Gypsum ($CaSO_4.2H_2O$) can also be used to improve the available Ca content of acid soils. In Cerrado soils, gypsum is recommended on the basis of clay content for annual crop production using the formula (Sousa and Lobato, 1996):

$$\text{Gypsum requirement (kg ha}^{-1}) = 50 \times \text{clay content (\%)}.$$

In addition to Ca, gypsum can supply S to growing plants and Ca can leach to subsoil

horizons where native Ca levels may be too low to support root growth. The ionic

Table 7. Response of upland rice and common bean grown in rotation to fertilization in Cerrado soil.(Fageria and Souza, 1995)

Fertlity level	Rice grain yield[1] ($kg\ ha^{-1}$)	Common bean grain yield[1] ($kg\ ha^{-1}$)
Low	1684b	1230c
Medium	2117a	1818b
High	2104a	2162a
Medium + green manure	2403a	1537a
F – Test	*	**

[1]Values are averages of three crops grown in rice-bean rotation.
*, ** significant at the 5 and 1% probability levels, respectively. Within same column, means followed by the same letter do not differ significantly at 5% probability levels by Tukey's test.
[2]Cerrado soil fertility levels for rice were low (no addition of fertilizers); medium (50 kg N ha^{-1}, 26 kg P ha^{-1}, 33 kg K ha^{-1}, 30 kg ha^{-1} (fritted glass material as a source of micronutrients); high (all the nutrients applied were double the medium level). *Cajanus cajan L.* was used as a green manure at the rate of 25.6 t ha^{-1} green matter. For common bean the fertility levels were low (without addition of fertilizers); medium (35 kg N ha^{-1}, 44 kg P ha^{-1}, 42 kg K ha^{-1}, 30 kg ha^{-1} (fritted glass material as a source of micronutrients) and high (all the nutrients applied were double the medium level).

strength of the soil solution is increased by gypsum, and this lowers the activity of Al^{3+}.

Furthermore, sulfate forms ion pairs such as $AlSO_4^+$ which is less toxic to plants than Al^{3+}. In some Cerrado soils, crop responses to applied S have been reported when sulfate-S is below10 mg kg^{-1} (Malavolta et al., 1987). These authors have also reported that crops are likely to benefit from the addition of S containing fertilizers at the rates of 20 kg S ha^{-1}.

Brazilian soils are generally low in available Zn and deficiency of this nutrient has been reported in upland as well as lowland rice, corn and soybean (Fageria et al., 1997a). Most of the Brazilian soils are acidic and liming is an essential practice for improving soil pH and decreasing the toxicity of elements such as Al and Mn. With higher pH, micronutrient cations form insoluble hydroxides or oxides and, under these circumstances, deficiency of micro-nutrients may be expected. A typical example is Fe deficiency in Brazilian Oxisols in upland rice when soil pH is raised to about 6 (Fageria, 1998). The best management strategy is to avoid over-liming the soil so that pH is maintained in the range 5.5 to 5.8. Application of Zn at about 2 to 5 kg ha^{-1} through zinc sulphate can correct Zn deficiency in most annual crops. Foliar spray of micro-nutrients is also effective.

4.3 Control of soil erosion

Water erosion is the main cause of top soil loss and decreased soil productivity of arable

Table 8. Yield and nutrient accumulations by various crops grown in four year rotation on an Oxisol in central Brazil. (Fageria, 1998)

Yield and	Upland Rice		Common bean		Corn		Soybean	
Nutrient	Shoot	Grain	Shoot	Grain	Shoot	Grain	Shoot	Grain
Yld kg ha^{-1}	6642	4794	1773	1674	13670	8148	2901	1323
N kg ha^{-1}	80	80	19	68	82	126	57	90
P kg ha^{-1}	4	9	1	5	5	17	8	9
K kg ha^{-1}	174	15	37	31	108	19	44	24
Ca kg ha^{-1}	27	2	21	5	34	8	48	5
Mg kg ha^{-1}	19	5	8	4	18	8	16	3
Zn g ha^{-1}	159	136	45	73	183	196	75	87
Cu g ha^{-1}	35	51	12	21	60	8	95	31
Mn g ha^{-1}	1308	395	91	17	366	81	269	27
Fe g ha^{-1}	523	148	398	129	974	163	1277	172
B g ha^{-1}	40	20	26	14	137	49	38	21

lands under Brazilian conditions. Top soil depth is a criterion that has been often used to evaluate soil quality and productivity. Erosion of top soil usually reduces plant-available water and nutrients. As topsoil depth decreases, so normally does soil productivity. Soil erosion can be reduced to a tolerable level by adopting erosion control structures and practices such as terraces, strip or contour cropping, and

conservation tillage. Table 9 shows soil and nutrient losses by water erosion under conventional and conservation tillage on an Oxisol from the state of Rio Grande do Sul. Soil and nutrient losses were much lower under zero-tillage as compared to conventional tillage system.

Table 9. Soil and nutrient losses by water erosion under different tillage systems in wheat-soybean rotation on a Brazilian Oxisol (Kochhann, 1990)

Tillage System	Soil loss ($t\ ha^{-1}\ yr^{-1}$)	Nutrient loss ($kg\ ha^{-1}$)
Conventional (residue burned)	12.8	54.4
Conventional (residue incorporated)	4.0	18.2
Zero-tillage	1.1	4.5

4.4 Improving soil organic matter content

Soil organic matter is linked to desirable soil physical, chemical, and biological properties and is closely associated with soil productivity. As a chemical reservoir, there is universal acknowledgement that soil organic matter is the major indigenous source of soil-available N, P, S and other essential nutrients. Some cultural practices such as incorporation of crop residues, use of organic manures, use of proper crop rotation and conservation tillage systems are important strategies for maintaining adequate levels of soil organic matter.

4.5 Use of crop rotation

Crop rotation has many advantages such as improving organic matter content, reducing incidence of insects, weeds and diseases, and reduced N fertilizer requirements for optimal grain yield when compared to monoculture. For crops following legumes, this reduction is often attributed to the additional N_2 fixed by legumes and that is released through decomposition of roots and residues. Furthermore, rotated crop sequences may potentially provide available soil N through increase in soil organic matter, soil microbial biomass, and mineralizable N. Selection and applicability of cropping systems is guided by climatic and economic principles. Specific crop rotation sequences are chosen for adaptability to the climate and soil of the area, performance in relation to other crops in the cropping sequence, and economic return. Choice of crop is greatly affected by the availability of water, which is generally determined by local environmental conditions. In Brazilian Cerrado soils, rice – common bean – corn – soybean is one of the appropriate crop rotations. Another crop rotation may be soybean – corn – rice – common bean. In these rotations, the first

crop is planted during the rainy season (October to March) and second crop is planted during dry season with irrigation (May to September).

4.6 Exploring plant genetic variability

Use of nutrient-efficient or tolerant crop species and/or cultivars can be a complementary solution for crop production on low fertility or acidic soils. Differences in the crop cultivars' use of N, P, and K have been reported by Fageria et al. (1988; 1990a; 1997a) and Fageria and Baligar (1997a) under Brazilian conditions. Similarly, Fageria and Baligar (2001) reported differences in Al tolerance of different crop species expressed on the basis of Al-saturation. Cassava, upland rice, cowpea and peanut are most tolerant to Al-toxicity and cotton, common bean, and mungbean are most sensitive.

5. CONCLUSIONS

Increasing crop yields is essential in order to keep pace with the food demands of an increasing world population. This can be achieved by either further increasing productivity on intensively cultivated land or by bringing new areas under cultivation. Both approaches can be used in South America and Africa where red soils are dominant and where food production needs to be dramatically increased. Most of the red soils are deep and have good physical properties except for their low water holding capacity. Climatic conditions in many red soils areas, especially in South America, are favorable, although seasonal drought in China is a serious constraint to the use of the red soils. Most red soils, although by no means all, are acidic and are very low in nutrients, especially phosphorus. To obtain high/or stable yields on these soils, the following management practices are suggested: (1) use of adequate rates of lime and fertilizers; (2) maintaining a regular, adequate supply of organic matter, if possible by use of organic manures on small holdings, or by use of green manure on bigger holdings; (3) use of proper crop rotation, with greater emphasis on increasing the area under pulses and forage legumes, so as to derive benefit from residual nitrogen fixed by them; (4) adoption of improved cultural practices to improve nutrient use efficiency; (5) use of efficient or tolerant cultivars in combination with soil amendments; (6) use of some infertile acid red soils with sandy texture for permanent pasture rather than crop production; (7) adoption of integrated nutrient management systems so as to improve nutrient use efficiency by annual crops and (8) adoption of soil conservation practices such as terracing, contour ploughing, use of cover crops, minimum tillage practices and increasing crop residues. All these measures are relevant to improving the productivity of the red soils of China but the point needs to be emphasized that whether or not such measures are taken up in practice depends as much, if not more, on socio-economic factors as on scientific and

technical solutions to the natural constraints on the use of the soils.

6. REFERENCES

Baligar, V. C. and Ahlrichs, J. L. 1998. Nature and distribution of acid soils in the world. P. 1-11. In:R. E. Schaffert (ed). *Develop a strategy for the Collaborative Research and Dissemination of Technology in Sustainable Crop Production in Tropical Acid Savannas and Other Problem Soils of The World.* Purdue University, W. Lafayette.

Baligar, V. C. and Fageria, N. K. 1997. Nutrient use efficiency in acid soils: Nutrient management and plant use efficiency. P. 75-95. In: In: A. C. Moniz, A. M. C. Furlani, R. E.Schaffert, N. K. Fageria, C. A. Rosolem, H. Cantarells (eds). Brazilian Soil Sci. Soc., Campinas, Brazil.

Bhattacharyya, A. K. 1992. Characterization, utilization and amelioration of Indian red soils. In *Proceedings of International Symposium on Management and Development of Red Soils in Asia and Pacific Region. (Dec. 3-15, 1990, Nanjing, China).* pp 13-14 Science Press Beijing, New York.

Carter, M. R., Gregorich, E. G., Anderson, D. W., Doran, J. W., Janzen, H. H. and Pierce, F. J. 1997. Concepts of soil quality and their significance. p.1-19. In: E. G. Gregorich and M. R. Carter (ed.) *Soil Quality for Crop Production and Ecosystem Health.* Elsevier, Amsterdam.

Dudal, R. 1976. Inventory of the major soils of the world with special reference to mineral stress hazards. P. 3-13. In; M. J. Wright (ed). *Plant Adaptation to Mineral Stress in Problem Soils.* Cornell University Press, Ithaca NY.

Eswaran, H., Reich, P. and Beinroth, F. 1997. Global distributions of soils with acidity. P. 159- 164. In: A. C. Moniz, A. M. C. Furlani, R. E. Schaffert, N. K. Fageria, C. A. Rosolem, H. Catarells (eds). Brazilian Soil Sci. Soc., Campinas, Brazil.

Eswaran, H., Beinroth, F.,and Reich, P. 1999. Global land resources and population-supporting capacity. *Am. J. Altern. Agric.* **14**;129-136.

Fageria, N.K. 1992. *Maximizing Crop Yields.* Marcel Dekker, New York.

Fageria, N.K. 1998. Annual report of the project: *The study of liming and fertilization for rice and common bean in cerrado region.* National Rice and Bean Research Center, Goiânia, Brazil.

Fageria, N. K. 2001. Effect of liming on upland rice, common bean, corn, and soybean production in cerrado soil. *Pesq. Agropec. Bras.* **36**:1419-1424.

Fageria, N.K. and Baligar, V. C. 1997.a Phosphorus use efficiency by corn genotypes. *J. Plant Nutr.***20**: 1267-1277.

Fageria, N.K. and Baligar, V.C. 1997b. Response of common bean, upland rice, corn, wheat, and soybean to soil fertility of an Oxisol. *J. Plant Nutr.* **20**:1279-1289.

Fageria, N. K. and Baligar, V. C. 2001. Improving nutrient use efficiency of annual crops in Brazilian acid soils for sustainable crop production. *Commun. Soil Sci. Plant Anal.* **32**:1303-1319.

Fageria, N. K., Baligar, V.C. and Edwards, D.G. 1990a. Soil-plant nutrient relationships at low pH stress. p.475-507. In: V.C. Baligar and R.R. Duncan (ed.). *Crops as Enhancers of Nutrient Use.* Academic Press, San Diego.

Fageria, N.K., Baligar, V.C. and Jones, C.A. 1997a. *Growth and Mineral Nutrition of Field Crops.* 2nd edition, Marcel Dekker, New York.

Fageria, N.K., Baligar, V.C., Wright, R.J. and Carvalho, J.R.P. 1990b. Lowland rice response to potassium fertilization and its effect on N and P uptake. *Fertilizer Res.* **21**:157-162.

Fageria, N.K. and Barbosa Filho, M.P. 1987. Phosphorus fixation in Oxisol of central Brazil. Fert. Agric. 94:33-37.

Fageria, N.K., Morais, 0.P., Baligar, V. C. and Wright, R.J. 1988. Response of rice cultivars to phosphorus supply on an Oxisol. *Fertilizer Res.* **16**:195-206.

Fageria, N. K. and Souza, N. P. 1995. Response of rice and common bean crops in succession to fertilization in cerrado soil. *Pesq. Agropec. Brasileira,* **30**:359-368.

Fageria, N. K., Wright, R. J., Baligar, V. C. and Carvalho, J. R. P. 1989. Upland rice response to

potassium fertilization. *Fertilizer Res.* **21**:157-162.

Goedert, W.J. 1989. Cerrado region: Agricultural potential and policy for its development. *Pesq. Agropec. Brasileira, Brasília* **24**:1-17.

He, Z. L., Yang X., and Baligar, V. C. 2001. Increasing nutrient utilization and crop production in the red soil
regions of China. *Commun. Soil Sci. Plant Analysis* **32:** 1251-1263.

Kiome, R. M. and Muchena, F. N 1998. Red and lateritic soils of Kenya: management for sustainable agriculture. p. 73- 84. In: J. Sehgal, W.E. Blum and K. S. Gajbhiye (ed). *Red and Lateritic Soils Vol 2. Red and Lateritic Soils of the World.* A. A. Balkema/Rotterdam, The Netherlands.

Kochhann, R.A. 1990. The Brazilian-Canada tillage project: The Brazilian perspective. p.1-12. In: CIDA and EMBRAPA-CNPT (ed). *Conservation Tillage for Subtropical Areas. Passo Fundo, Rio Grande do Sul, Brazil.*

Macedo, J. 1995. *Prospective for the rational use of Brazilian cerrado for food production.* EMBRAPA-CPAC, Planaltina, Brazil.

Malavolta, E. P., Vitti, G. C., Rosolem, C. A.; Fageria, N. K. and Guimaraes, P. T. G. 1987. Sulphur responses of Brazilian crops. *J. Plant Nutr.* **10**: 2153-2158.

Moncharoen, L. 1992. Red soils of Thailand. In *Proceedings of International Symposium on Management and development of Red Soils in Asia and Pacific Region (Dec. 3-15, 1990, Nanjing, China).* pp 21-26. Science Press, Beijing and New York.

Rahman, M. R. 1992. Characteristics, management and development of red soils in Bangladesh. In *Proceedings of International Symposium on management and development of Red Soils in Asia and Pacific Region (Dec.3-15, Nanjing China)* pp 112-116. Science Press, Beijing and New York.

Raij, B.V. and Quaggio, J.A. 1997. Methods used for diagnosis and correction of soil acidity in Brazil: an overview. p.205-214. In: A.C. Moniz et al. (ed). *Plant Soil Interaction at Low pH.* Brazilian Soil Science Society, Campinas, Brazil.

Saheed, S. M. 1992. Red soils of Bangladesh: distribution, development and properties. In *Proceedings of International Symposium on management and Development of Red Soils in Asia and Pacific Region (Dec. 3-15, 1990, Nanjing, China).* pp 30-37. Science Press, Beijing and New York.

Sanchez, P. A. 1976. *Properties and Management of Soils in the Tropics.* John Wiley and Sons, New York.

Sanchez, P. A., Isbell, R. F. 1978. A Comparison of soils of tropical Latin America and tropical Australia. In: P. A. Sanchez and L. E. Tergas (ed). *Pasture Production in Acid Soils of the Tropics.* CIAT, Cali, Colombia. p. 25- 53.

Sanchez, P.A and Salinas, J.G. 1981. Low-input technology for managing Oxisols and Ultisols in tropical America. *Adv. Agron.* **34**:279-406.

Scoopa, C. O. and Godagnone, R. 1998. Red soils of Argentina: Concept, distribution,use- management and future challenges. p.85- 91. In: J. Sehgal, W.E. Blum and K. S. Gajbhiye (ed). *Red and Lateritic Soils Vol 2. Red and Lateritic Soils of the World.* A. A. Balkema/Rotterdam, The Netherlands.

Sehgal, J. 1998. Red and lateritic soils: An overview. P. 3-9 In:J. Sehgal, W.E. Blum and K. S. Gajbhiye (ed). *Red and Lateritic soils Vol 1. Red and Lateritic Soils of the World.* A. A. Balkema/Rotterdam, The Netherlands.

Sehgal, J. , Blum, W.E. and Gajbhiye, K. S. (ed). 1998a.*Red and Lateritic Soils Vol 1. Red and Lateritic Soils of the World.* A. A. Balkema/Rotterdam, The Netherlands.

Sehgal, J. , Blum, W.E. and Gajbhiye, K. S. (ed). 1998b.*Red and Lateritic Soils Vol 2. Red and lateritic Soils of the World.* A. A. Balkema/Rotterdam, The Netherlands.

Sehgal, J. Challa, O. Thampi, C. J. Maji, A. K. and Nag Bhushana, S. R. 1998c. Red and lateritic soils of India. P. 1- 18. In:J. Sehgal, W.E. Blum and K. S. Gajbhiye (ed). *Red and Lateritic soils Vol 2. Red and Lateritic Soils of the World.* A. A. Balkema/Rotterdam, The Netherlands.

Soil Science Society of America. 1996. *Glossary of Soil Science Terms.* Soil Science Society of America, Madison, WI, 134p.

Soil Survey Staff. 1999. Soil Taxonomy: Basisc System of Soil Classification for Making and Interpreting Soil Surveys. USDA- Natural Resource Conservation Service, Washington, DC, 869p.

Sousa, D.M.G and Lobato, E. 1996. *Soil amendment and fertilization for soybean growth in cerrado soils.* 30p. (EMBRAPA-CPAC. Technical Circular, 33).

Sudjadi, M, Subagjo, H and Adiningsih, J. S. 1992. Red soils in Indonesia: Problems and managagement. In *Proceedings of International Symposium on Management and Development of Red Soils in Asia and Pacific Region (Dec. 3-15, Nanjing, China).* pp 21-26. Science Press, Beijing and NewYork.

Toan, B. Q. 1998. Reddish ferallitic soils of Vietnam. P.67-71. In: J. Sehgal, W.E. Blum and K. S. Gajbhiye (ed). *Red and Lateritic soils Vol 2. Red and lateritic Soils of the World.* A. A. Balkema/Rotterdam, The Netherlands.

Van Wambeke, A 1992. *Soils of the Tropics,* McGraw-Hill, Inc. New York

Von Uexkull and Mutert, E. 1995. Global extent, development and economic impact of acid soils. *Plant and Soil* **171**: 1-15.

Wahab, N. A and Zahari, A. B. 1992. Distribution, characterization and utilization of red soils in Peninsular Malaysia. In *Proceedings of International Symposium on Management and Development of Red Soils in Asia and Pacific Region (Dec. 3-15, Nanjing, China).* pp 27-29. Science Press, Beijing and New York.

Wander, M. M., Walter, G. L., Nissen, T. M., Bollero, G. A., Andrews, S. S. and D. A. Cavanaugh-Grant. 2002. Soil quality:Science and process. *Agron. J.* **94**;23-32.

Xiong, L. M. and Lu, R. K. 1996. Nutrient stress in red soils of China. p. 339- 351. In: J. Sehgal, W.E. Blum and K. S. Gajbhiye (ed). *Red and Lateritic Soils Vol 2. Red and Lateritic Soils of the World.* A. A. Balkema/Rotterdam, The Netherlands.

Zhao, Q. 1996. Red soils of hilly region in China: ecological environment and strategies for integrated development. p. 53- 58. In: J. Sehgal, W.E. Blum and K. S. Gajbhiye (ed). *Red and Lateritic Soils Vol 2. Red and Lateritic Soils of the World.* A. A. Balkema/Rotterdam, The Netherlands.